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Development of the Augmented Musculature Device

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Abstract

We developed an Augmented Musculature Device (AMD) that assists the movements of its wearer. It has direct application to aiding military and law enforcement personnel, the neurologically impaired, or those requiring any type of cybernetic assistance. The AMD consists of a collection of artificial muscles, each individually actuated, strategically placed along the surface of the human body. The actuators employed by the AMD are known as "air muscles" and operate pneumatically. They are commercially available from several vendors and are relatively inexpensive. They have a remarkably high force-to-weight ratio—as high as 400:1 (as compared with 16:1 typical of DC motors). They are flexible and elastic, even when powered, making them ideal for interaction with humans.

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Introduction

We developed a proof-of-concept prototype of an Augmented Musculature Device (AMD), an upper-extremity robot with direct application in security force augmentation and physical rehabilitation. The AMD is less expensive, more portable, and more capable than existing rehabilitation robots, and no commercial protective force assist device of this type yet exist.

Current state of the art in physical therapy robotics

As there are currently no workable exo-skeletal-type soldier assist systems, comparison of the AMD with the state of the art will necessarily be limited to the health-care field. To date, incorporating robots into physical therapy as a tool for the therapist has largely been a pioneering endeavor with a research focus. This work has shown a significant benefit resulting from employing robots in the process of rehabilitating individuals who have suffered a stroke. (Volpe et al., 2000) However, the physical size, and cost of current robots are significant barriers to their widespread distribution. Furthermore, current robot designs generally incorporate a very limited number of degrees of freedom—two is common. In contrast, the AMD has as many as seven degrees of freedom per arm, three at the shoulder, one at and elbow, and three at the wrist allowing it to assist a wide variety of complex, natural human arm motions. The low cost, ease of portability, and ability to facilitate complex movements gives the AMD a versatility previously unachieved in rehabilitation robotics. It will allow robotic therapy tools to reach more patients and to have a greater effect.

Robotic therapy in stroke rehabilitation has facilitated significant recovery in patients, even in chronic patients that are generally considered to have stabilized and are not expected to improve (Fasoli et al., 2004). Robots are capable of delivering far greater dosages of therapy than unaided therapists, simply because they do not tire. Robotic therapy tools also provide high-precision measurements of patient impairment, based on kinematic and dynamic data recorded during therapy sessions. (Krebs et al., 1998) These measures are currently being used as powerful tools in a quantitative, science-based approach to the study of recovery from neurological injury. (Krebs et al., 2002)

These benefits make it desirable to distribute stroke robots and make them as widely available as possible. Not only would this provide better therapy and more complete recovery to a larger population, but it would also allow for the collection of recovery data on a larger group of subjects and increase the rehabilitation community's understanding of the progression of therapy, which in turn would allow for therapy better matched to the patient, which would lead to more complete recovery, etc. Unfortunately there are currently several barriers to stroke robot distribution.

Currently existing stroke robots were typically developed as laboratory research tools. In the early days of robotic therapy it was unknown what robot capabilities would be critical and which variables would be of the most interest. As a result, the robots were conservatively designed with power output, precision, and sensing capabilities in excess of what is required during therapy. Conservative designs had other secondary effects. The size and weight of the actuators made it difficult to implement additional degrees of freedom, limiting the complexity of robot-aided movements. The robots as a whole are bulky, heavy, and difficult to transport. And the robots are quite expensive to make.

MIT-MANUS, developed nearly ten years ago (Hogan et al., 1995), has been used extensively in clinical trials with over 100 patients. The application and design philosophy of MIT-MANUS matches that of the Agile Rehabilitation Robot more closely than other currently-existing stroke robots and therefore provides the clearest basis for comparison. MIT-MANUS consists of two direct-drive motors and an arm linkage that can produce planar movement of the arm cradle at the endpoint (see Figure 1). Patients operate the robot by placing their impaired arm in the cradle, sitting opposite the robot, and attempting to move their arm in response to visual stimuli presented on a computer monitor (see Figure 2). The complete system consists of the robot, an endtable-sized electronics box, an adjustable table and chair, a PC and two monitors. It requires the coordinated efforts of several able-bodied adults to transport. MIT-MANUS and its successors in production at the company Interactive Motion Technology (IMT, 2003) are capable of two-dimensional planar arm motion only, although devices for vertical motion (Buerger et al., 2001) and three degree-of-freedom (dof) wrist rotation (IMT, 2003) are in various stages of development or production. The approximate price for the two dof robot system is $80,000.

Research using the “Assisted Rehabilitation and Measurement Guide” (ARM Guide) was first reported in (Reinkensmeyer et al., 1999). The ARM Guide has two degrees of freedom (dof), one with controlled damping and the other fully actuated. The actuated dof produced a trombone-like motion, and the motor used to actuate it allowed the patient some degree of control over their motion, similar to the motors in MIT-MANUS. The primary uses of the ARM Guide are to measure passive and voluntary ranges of motion, and to provide information about the magnitude and direction of forces directed into constrained dof’s (see Figure 3). As is visible from figure 4, the ARM Guide is large in relation to the limb it is exercising, and it appears to have a large mass.

A prototype robotic system with rehabilitation applications called the Mirror-Image Motion Enabler (MIME) was developed by Lum et al. (1999) and employed in several experiments. MIME consisted of two arm splints that allowed movement in the horizontal plane; one of the splints was instrumented and the other was attached to an 6 dof commercial PUMA robot (see figures 5— 6). Movement of the instrumented splint was sensed, and the robot moved the second splint to mirror it. Although the robot was capable of six dof movement, patient movement was limited to the plane by the splints. In contrast to MIT-MANUS and the ARM Guide, MIME does not allow the patient to displace the robot

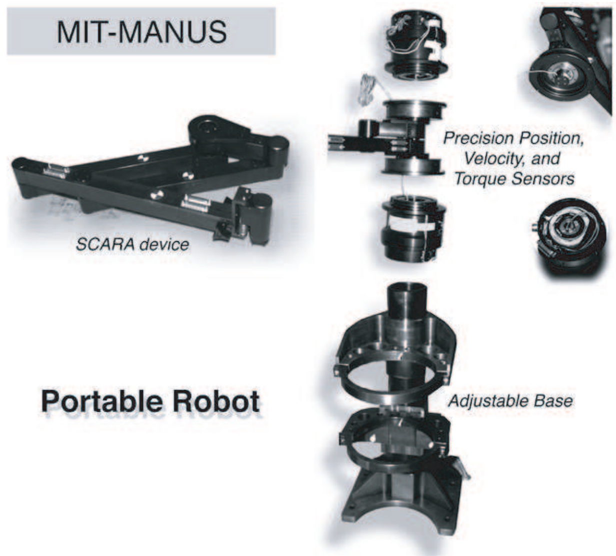

Figure 1. MANUS 2, exploded view. Reproduced from (Hogan, 2003)

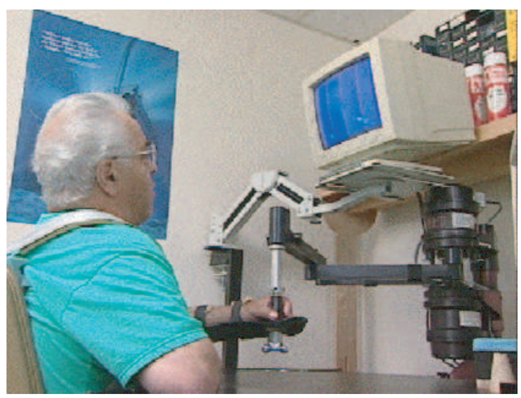

Figure 2. MANUS 2 in a clinical setting.

motion away from its controlled trajectory. The PUMA, as is typical of commercial robots, provides rigid position control. This limits the usefulness of MIME as a therapy aid.

As robotic therapy has gradually become better understood, it has become easier to design closer to the minimum requirements for an effective therapy robot. Doing this will yield a machine that is smaller, lighter, more mobile, and less expensive. This in turn will greatly facilitate the distribution of stroke robots and their accessibility to small clinics and individuals.

The AMD we proposed to develop is revolutionary in its approach. It is lighter than existing deigns, has a smaller footprint, has more degrees of freedom, and has less expensive componentry. It operates on a biologically motivated concept: it employs muscles

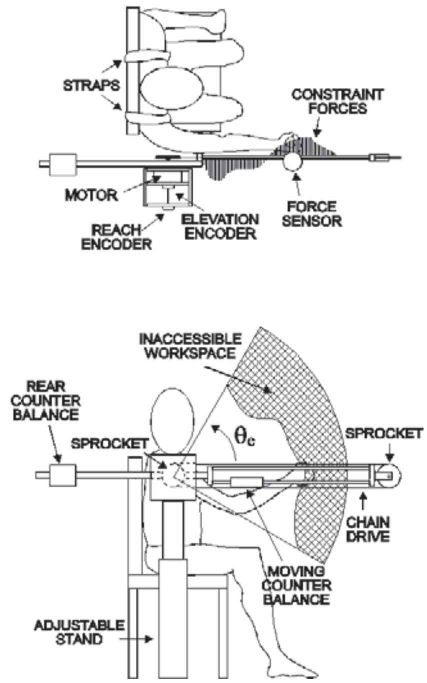

Figure 3. The ARM Guide. Reproduced from (ARM Guide, 2003)

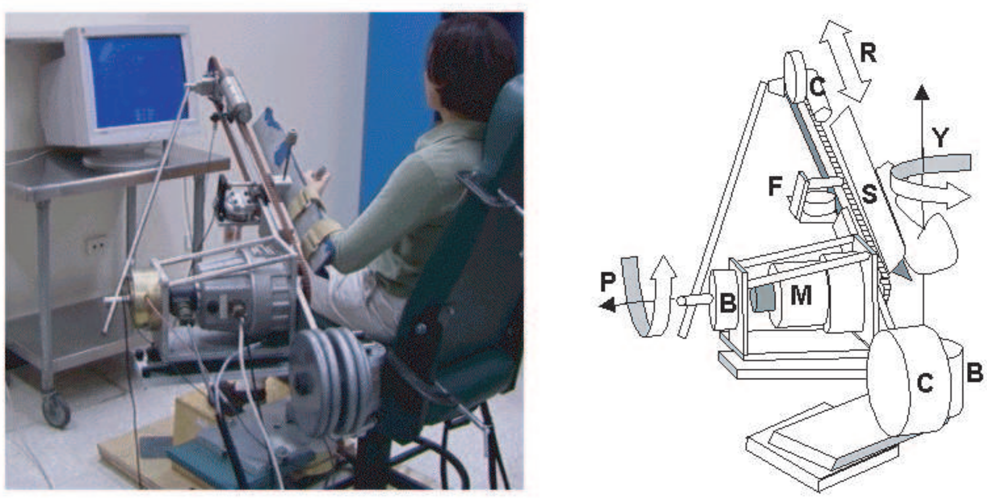

Figure 4. The ARM Guide. Reproduced from (Reinkensmeyer et al., 2000)

contracting about the skeletal system to produce moments about joints. It saves on weight, fabrication cost, and complexity by utilizing the patient's skeletal system, and simply overlaying a system of artificial muscles. See Figure 7 for a conceptual illustration of the AMD.

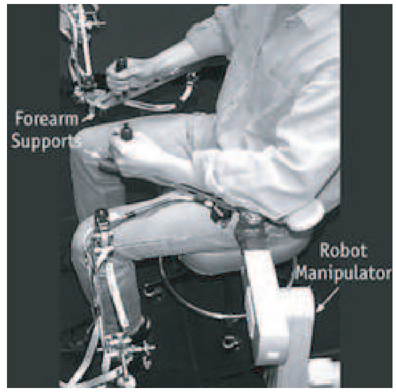

Figure 5. Reproduced from (Mirror-Image Motion Enabler (MIME). Burgar et al., 1996)

Figure 6. Mirror-Image Motion Enabler (MIME). Reproduced from (Burgar et al., 2000)

Subsystems

The Augmented Musculature Device (AMD) was specifically designed to exploit a rare set of properties found in a unique actuator technology. Therefore, the Methods discussion will

Figure 7. Conceptual illustration of the AMD

start with the actuators, then move to other aspects of the hardware and software, including the inherent and added safety features of the AMD.

Actuators

The actuators are air muscles or "McKibben" muscles, named after Joseph L. McKibben, and American physician who invented them in the 1950's. and they operate on a simple concept. A Mckibben muscle consists of a rubber bladder, contained within a helical net of fibers that resembles a bamboo finger trap—as the diameter of the bladder increases, the net forces the assembly to grow shorter. This shortening is used to simulate the contraction of a muscle. See Figure 8.

Figure 8. Model of the air muscle sheath's braided structure

The McKibben muscles are operated pneumatically. Each one requires a pressurized air source (50 psi), connecting tubing, and a three-way valve to let high pressure into the muscle (contraction) and to vent the muscle to atmosphere (relaxation). One of the advantages of a McKibben muscle approach is that the heaviest and bulkiest part of the system, the pressure source and accumulator, can be shared by all actuators, resulting in a decreasing weight per actuator as the number of actuators increases. This is in contrast to the electric motors used in existing stroke robots, each of which requires a separate amplifier.

McKibben muscles have the distinction of having one of the highest power-to-weight ratios of any commercially available actuator technology, as high as 400:1 (compare with 16:1 typical of DC motors). (Shadow Robot Co., 2003)

The McKibben muscles operate only in tension, not in compression. All that is required to integrate them into a robotic system is two insertion points, one for each end. The muscles don't even need a direct path between the two insertion points; they are compliant and will conform to whatever geometry lies between, snaking through passages and bending around corners. Air muscle geometry (insertion points) is determined in part by the fact that the air muscle's useful operating range is small. It loses most of its contraction force by the time is has contracted to 75% of its stretched length. That requires the moment arm about the axis of rotation to be relatively small, for motions with large ranges.

Fabric frame

We attached the McKibben muscles securely to a fabric frame that will be donned and doffed by a stroke patient with some assistance. Construction will be such that, for the most part, the end of one McKibben muscle is connected directly to another, so that the muscles are exerting tension primarily on each other rather than on the fabric. Exceptions to this include muscles nearest the wrist and nearest the chest. In these cases, the muscles are securely connected to the fabric in such a way that the load is distributed throughout the fabric weave. This is accomplished by means of sewing fabric anchors at appropriate locations. Sewing allows for lightweight and compliant, yet strong connections. Sewn joints are common even in safety critical applications such as rock climbing equipment, and appropriately sewn nylon joints can exceed 20kN in tensile strength.

The fabric shirt was constructed so that it can be wrapped onto a patient, i.e. arms and head will not have to pass through sleeves and neck holes. This will be helpful for patients with accompanying medical equipment such as breathing tubes. When donning the robot the fabric will wrap around the patient's arm, palm, and torso, so that the shirt will be able to support the tension of the McKibben muscles. The shirt will be fastened on with velcro hook-and-loop closures.

Safety by design

Many safety concerns are avoided by the nature of the hardware. One key point in which the ARR differs from existing rehabilitation robots is that it has no rigid members. The actuators are soft and compliant. There are no rigid links to impose kinematics of movement. As a result there are also no pinch points and no sharp corners. The ARR accomplishes this by utilizing the body's own skeletal structure to define the kinematics of robot movement.

Another consequence of having no rigid members to define the robot kinematics is that the ARR can have a fraction of the weight of traditional robots. Lower weight means that for a given movement speed, it has a lower kinetic energy. This lessens the risk of injury by being struck with the robot. Combined with the fact that the robot is comprised of soft materials–mostly fabric, plastic mesh, and rubber–greatly decreases the danger of being harmed by the moving robot.

The nature of the actuators themselves also contribute to the safety of the ARR. The actuators and pneumatic transmission lines have inherent damping that takes energy out of the system during each motion. This smoothes and softenes the resultant motions and restricts its ability to move very suddenly or to oscillate wildly. In industrial and commercial robots, damping is often added after the fact, either in hardware or in software, to stabilize controlled mechanical systems and prevent undesirable behaviors. It is an integral part of the ARR.

Also, the maximum force output is limited by the actuator size and the operating pressure. Both will be chosen carefully so that the maximum available force output matches as closely as possible the required operating force, making it impossible for unexpectedly large forces to be generated.

In addition, air muscles' ability to exert force declines dramatically as they contract. At 70% of their original length, their force production capacity is only a few percent of what it was at full length. While this allows adequate actuation for normal operation, it prohibits the robot from drastically changing the position of the arm (hyperextending the elbow for instance). The air muscles' limited range of motion keep the robot in a natural configuration.

Remaining safety concerns and safeguards

There are still a few conceivable failure modes for the McKibben muscles and the ARR. These are listed below with appropriate safeguards.

- Detachment of one end of the muscle from the fabric. Sudden detachment of the the muscle may possibly cause the muscle to snap about its other anchor point, propelling its free end at high velocities. In order to prevent this, muscles will be covered by a fabric sheath, which will be sewn on to the sleeve. In addition, subjects using the robot will be required to wear a hockey-style helmet with transparent face shield in order to further protect sensitive areas of the body.

- "Herniating" of the rubber hose through the plastic mesh followed by ballooning and popping. This condition typically occurs when McKibben muscles are routed over sharp corners and repeatedly abraded. The plastic mesh becomes separated and allows the rubber to balloon through the resulting gap. Although failure of this type is unlikely in the ARR, flying debris caused by popping of the rubber would be contained by the sewn fabric sheaths surrounding the muscles. The helmet and face shield would provide further protection, as well.

- Puncture of the rubber hose by a sharp object. Puncture of the rubber hose while it is still within the plastic mesh has been observed to produce only a noisy hissing and a decrease in muscle performance (Shadow Robot Co., 2003).

- Detachment of the air supply hose from the muscle. Detachment of the air supply hose at any point will only result in a loss of power to the muscle and a venting of the air supply. The 50psi supply will not produce airflow velocities that could cause harm, and the tubes will be prevented from whipping around by being bound together at frequent intervals into a single pneumatic umbilical.

- Failure of a valve to close or open. Each muscle has two valves: one for inflation and one for deflation. If either fails, a muscle will produce an undesirably high or low amount of force, likely creating undesirable movement. In order to prevent the patient from being stricken by his or her own arm under these conditions, a nylon strap will be attached from the wrist to a point on the table opposite the patient, and will be adjusted to preclude the possibility of a patient reaching his or her own head or face. In addition, two E-stop buttons will be provided to the patient and therapist that will, through a hard-wired circuit, immediately remove power from the inflation and deflation valves, arresting all robot-driven motion. Inflation valves will be normally closed and deflation valves will be normally open, so that removal of power will both isolate the muscles from the pressurized air supply and vent whatever pressure they have to the atmosphere, causing the ARR to go limp. The E-stop safety feature is independent of the computer, although the computer will sense when it has occurred and will shut down the control programs.

Compressed air delivery system

The pressure system for the Augmented Musculature Device (AMD) supplies compressed air to its air muscle actuators. In consists of a compressed gas cylinder (securely anchored to the wall), regulator, relief valve, and shutoff valve, which together will supply pressurized air of less than 60 psi. This compressed air supply is then piped through polyurethane tubing through a bank of three-way valves, which will direct it intermittently to air muscle actuators. See Figure 9.

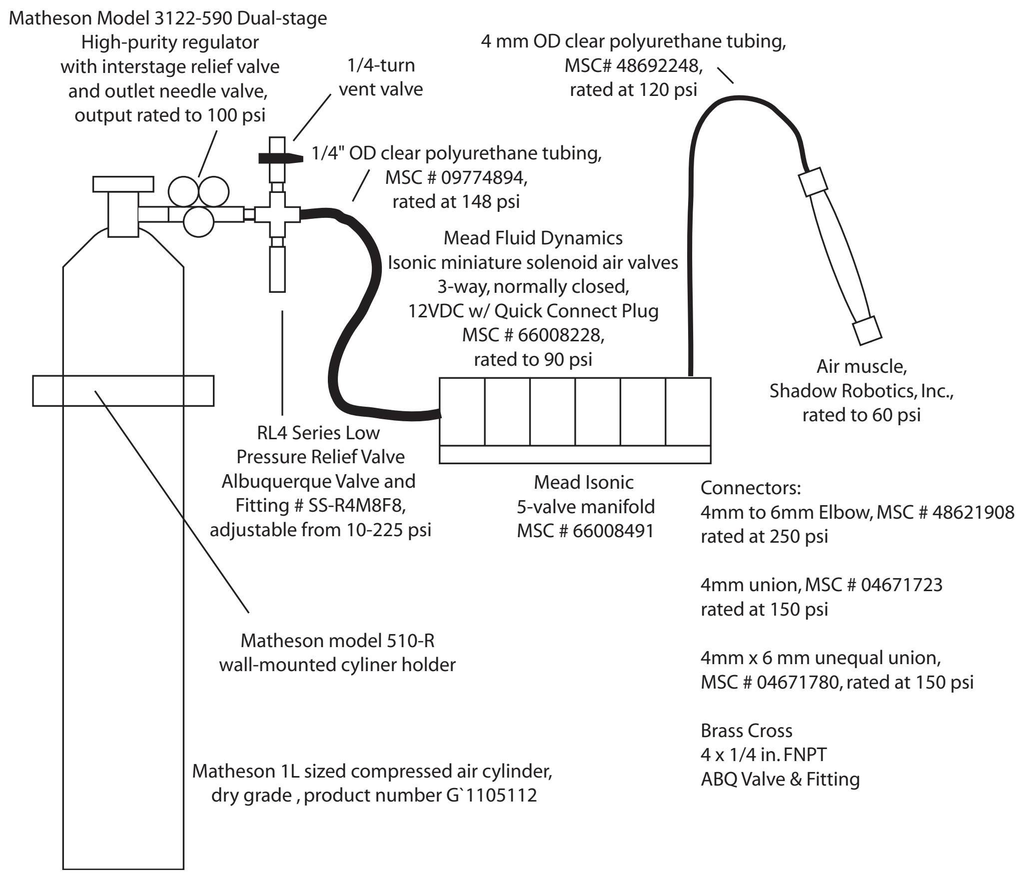

Figure 9. Compressed air system diagram

All components are rated for use at 60 psi or higher. Failure of the air muscles results in a hiss or a pop, but does not produce flying debris due to the enclosing mesh. If any tubing becomes disconnected, the flow rate through the 4- or 6-mm diameter will not be sufficient to cause direct harm. In order to prevent a disconnected tube from striking an eye, protective eyewear will be required for all observing the system.

Electrical system

The digital output from the PC's data acquisition board is incapable of directly switching the servo-driven three-way valves. Each DIO channel is capable of sourcing +32 mA at 3.0 V and sinking -64 mA at 0.0 V. whereas the valves require 133 mA at 12V. As a result, a bank of FET switching circuits has been constructed to overcome this limitation. See Figure 10.

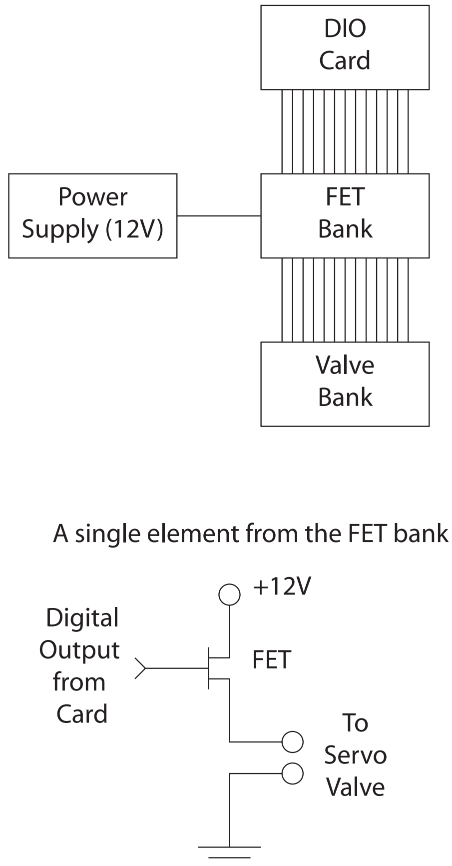

Figure 10. Electrical interface between the DIO board and the power electronics.

Development/Construction

Feasibiltiy testing

The initial goal was simply to validate that air muscle technology is likely to be a viable actuator for this application. A single air muscle was inserted as a bicep on the mannequin and manually actuated. It produced elbow flexion over a range of about 80 degrees. (The mannequin is physically limited to about 90 degrees.) Air pressure in the system was limited to 20 psi, rather than the 90 psi that the air muscles are rated for.

The largest unexpected challenge encountered was friction in the elbow joint and between the muscle and the arm. (See Figure 11.) Ideally, the whole system would have no static friction, and its viscous friction would come only from viscoelastic behavior in the muscles. Friction was decreased by sanding the quasi-spherical seating surface and loosening the elbow joint by one turn. Problematic is that the male spherical surface on the lower arm is actually not spherical at all, but egg-shaped. This will have to be addressed more fully in subsequent phases.

Figure 11. A wooden mannequin with an air muscle "bicep".

Each subsequent version is based off a wooden dummy rigged with muscles. Holes were drilled in the dummy with eyelets placed on key muscle groups, based of the human anatomy. This dummy predicted where muscles would need to be attached on the suit to obtain the desired movement. (See Figures 12–15.)

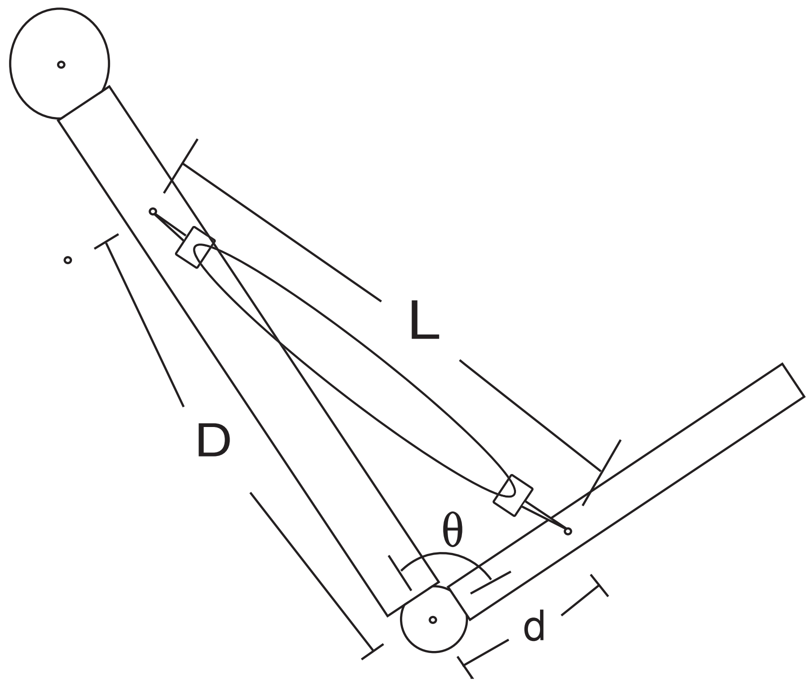

Figure 12. Model of muscle insertion for use in determining attachment points

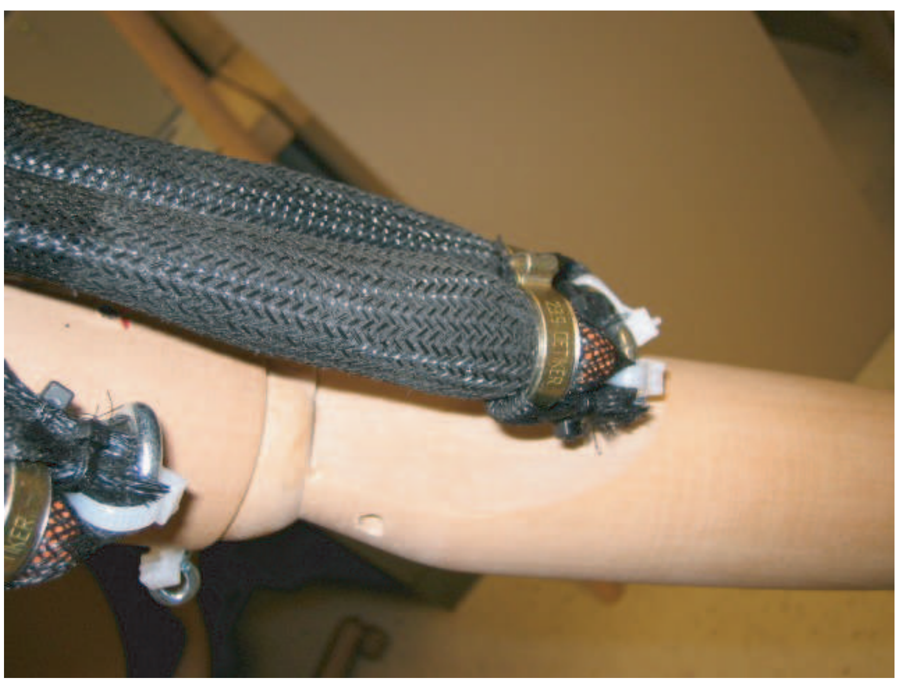

Figure 13. Method of attaching air muscles to the mannequin

Figure 14. Mannequin outfitted with an array of air muscles

Figure 15. Muscled mannequin, side view

Tubular webbing-based frame

The first interpretation of the AMD consisted of tubular webbing (using in climbing) sewn together to make adjustable straps. Muscles were then attached to the webbing extending to a collar, a chest strap, and wrist straps. This completely homemade suit was less effective than hoped for. The flimsy nature of the tubular webbing allowed for the desired range of movement, but lacked the necessary support for the muscles causing the suit to slide on the body. Other flaws include the restriction cause by the Velcro on the adjustable straps, although permitting desired adjustability the Velcro could not withstand the expanding forces without shifting in undesired directions. Although not a total success, this first suit emphasized the need for longer muscles and for the muscles to work in groups. Structurally the suit needed to be securer, enabling the muscles to pull in unison to keep the harness in place.

Motocross protective gear-based frame

Learning from the first suit the next direction was toward a pressure suit, to solve the structural stability problem. These suits are used by motor-cross riders to prevent overextension; the suits are form fitting with molded plastic on the shoulders, the forearms, and spine. (See Figures 16–18.) Initially the plastic protectors served to help attach the muscles to the suit, and the spine helped to provide leverage (excellent in preventing chocking). The suit gave the muscles greater range of motion, but efficiency was lost when the fabric sleeves slid up the arm and defeated the effort of the muscles. Additionally there was difficultly putting on the suit with its long sleeves. Attempting to correct the problem of the sliding sleeves they were removed. Two different approached were taken to create a type of fixed sleeve, both molding foam and leather were used.

Figure 16. Motocross frame and air muscles

Figure 17. Muscled motocross frame, side view

Figure 18. Arm muscle layout in the motocross frame

Molding Foam

Molding foam is most often used in medicine for splints, because it forms to the curvature of the human body and stays like an exoskeleton. This seemed ideal for AMD because it allowed increased comfort for the wearer and stability for the muscles. Molding foam forearms and biceps were made and attached to the body using Velcro. Muscles were then extended from the trunk of the pressure suit to the molding foam. The result was a big increase in movement. Although this suit was more access able to the wearer it still had a moderate discomfort level and the muscles over the shoulder would slip off. This slippage changed the direction of the desired movement, a clear inefficiency. Overall the molding foam arms allowed for more effective attachment points, minimized slippage and increased comfort. Nevertheless, it fell short of the anticipated result.

Leather

Leather was chosen to resolve the issues comfort and custom fit. (see Figure 19 This approach was derived from medieval armor. A custom fit was desired to help reduce and slip factor. Spandex was sewn to leather and secured to the arm with Velcro. The spandex protected the arm from the Velcro and allowed for arm size variety, then the Velcro was use to further secure the arm piece. Unlike the molding foam the leather arm was one piece, this was an improvement because the arm muscles were able to work as a group and increase the range of motion. The leather was stiff enough to support the muscles, which were attached with zip ties.

The changes in the suit resulted in increased stability, increased comfort and accessibility, and more muscle movement. However the problem of the muscles sliding off the shoulders still remained. To correct this problem elastic was strategically sewn into the suit on the shoulder and back. However this did not work, but created a shifting in the suit. To remedy this problem a new approach was taken one inspired by medieval armor.

Ballistic vest

The ballistic vest, in combination with the leather sleeves, solved the problems posed by previous attempts at the AMD. It provides stable shoulder support for the muscles, (see Figure 20) it has Velcro to fasten it securely around the waist, it is easy to put on and comfortable to wear. Special one way snaps covering the vest keep the muscles in place and allow muscle attachment at virtually any point in the front or in the back. (See Figures 21 and 22) This has minimized slippage, due to the stability of the vest. To completely solve the problem of muscles falling off the shoulders, fabric was sewn to the shoulders and neatly keeps the muscles in place. This, in combination with the leather sleeves, allowed for optimal arm movement.

Figure 19. Leather elbow section

Figure 20. Elastic straps for maintaining the muscles' position over the shoulder.

Figure 21. Array of snaps on the ballistic vest

Figure 22. Method of anchoring air muscles to the ballistic vest.

Conclusion

In the course of this LDRD, we demonstrated the feasibility of the AMD as an inherently safe, relatively unobstructive assistive device for military, security, and rehabilitation applications. However, the device itself is in its infancy and we look forward to furthering its development in the future.

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